Precision Astrometry with SIM PlanetQuest: Science and Mission Update

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for

Stephen Unwin

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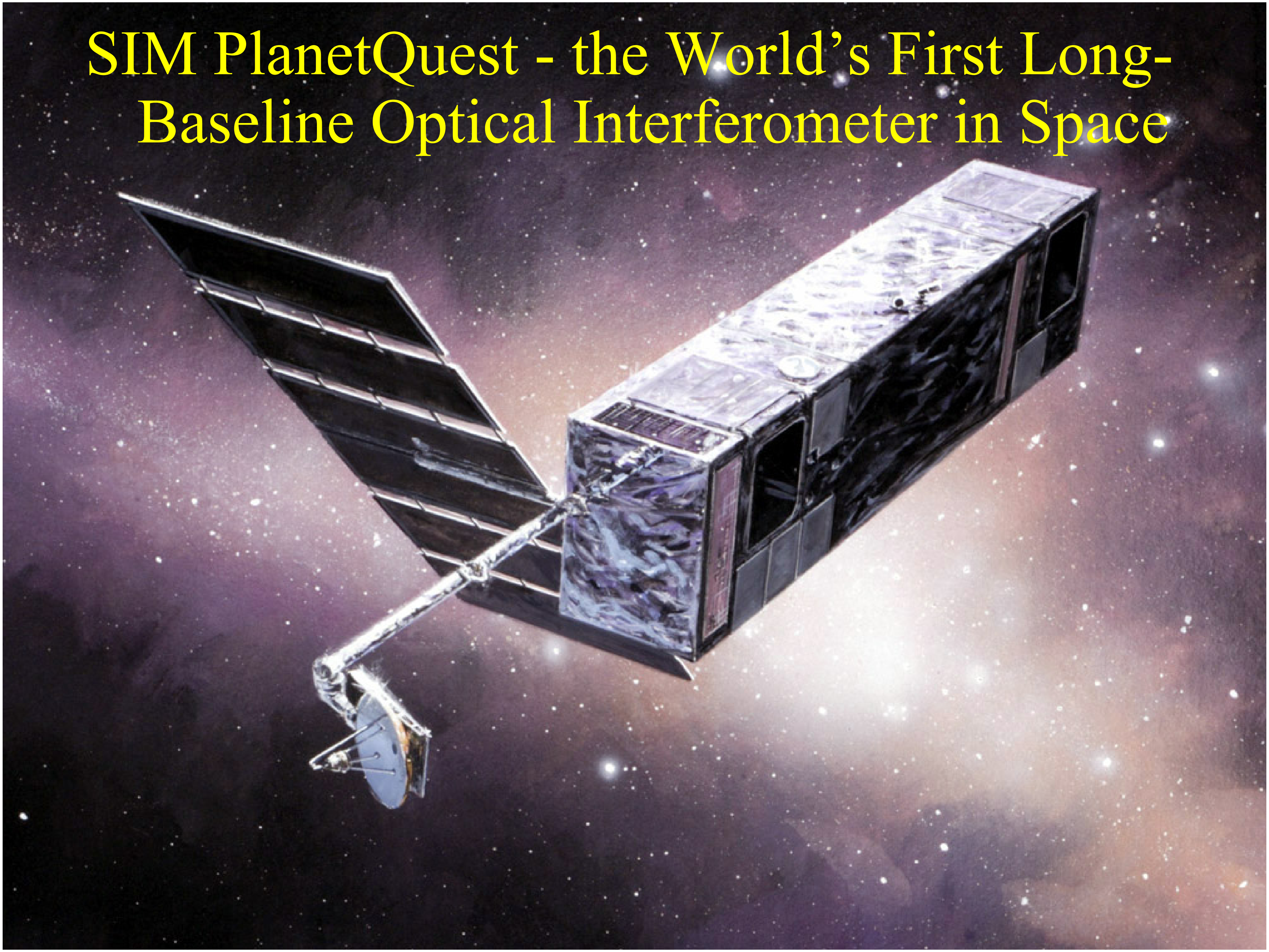
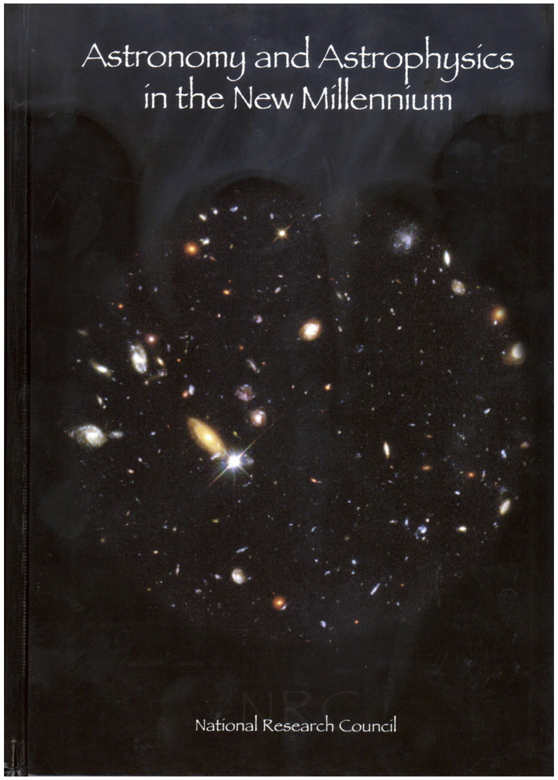

SIM PlanetQuest - the World's First Long-Baseline Optical Interferometer in Space

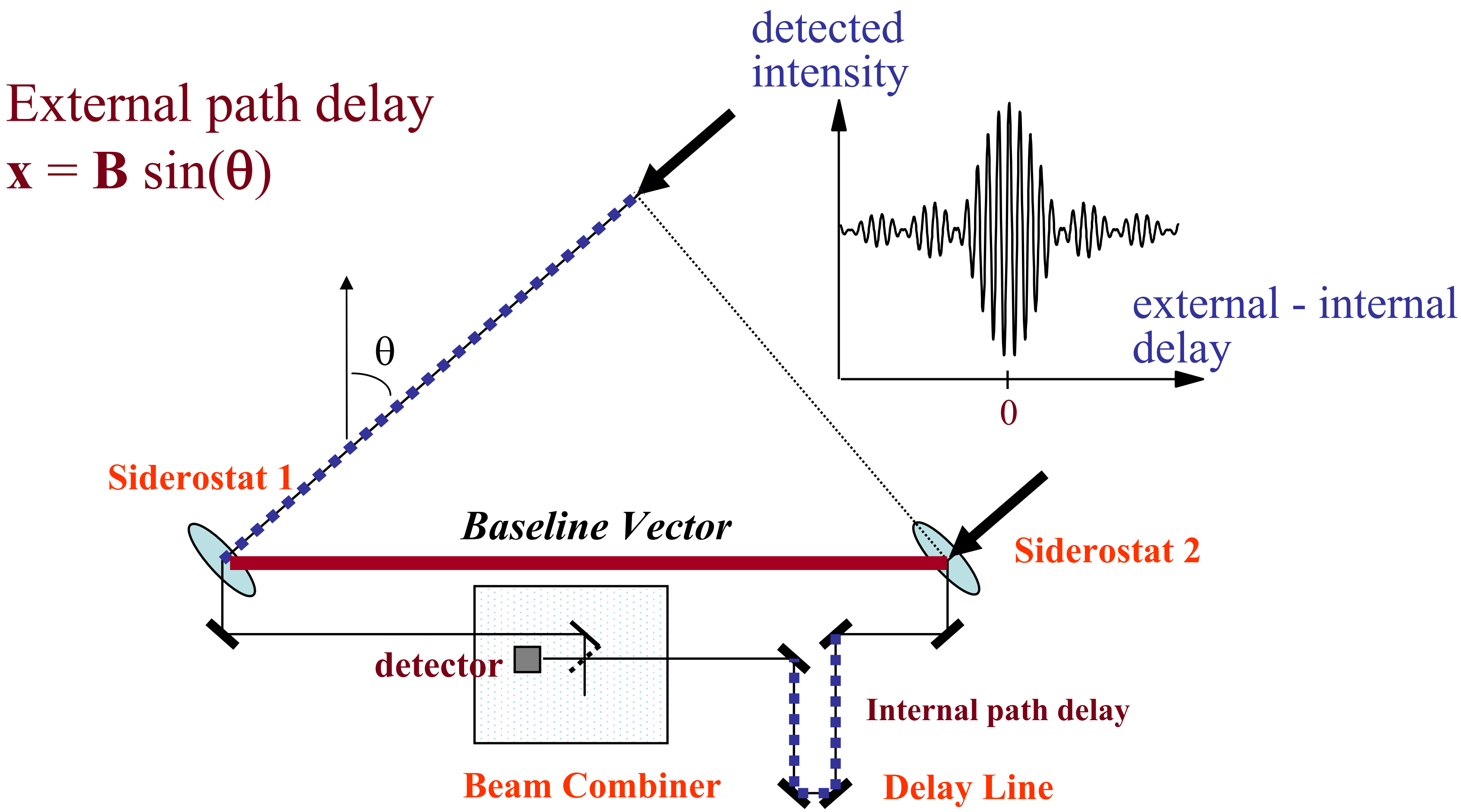
National Academy of Sciences / NRC endorses SIM PlanetQuest

- Decadal (Bahcall) Review endorses SIM (1991)
  - *"… would permit definitive searches for planets around nearby stars"*
  - *"… trigonometric distances throughout the galaxy"*
  - *"… would demonstrate the technology required for future missions"*
- Decadal (McKee & Taylor) Review (2001)
  - *"…reaffirms the 1991 NRC Committee by endorsing the completion of AIM [now called SIM]"*
  - *"… enable the discovery of planets much more similar to Earth in mass and orbit than those detectable now"*
  - *"…survey the Milky Way 1000 times more accurately than is possible now"*
- CAA reaffirms scientific importance of SIM (2002)
  - *"The CAA reaffirms the scientific excitement of the 2001 AASC for the important new planet-finding narrow-angle science capability of SIM."*



2001 NRC Decadal Review

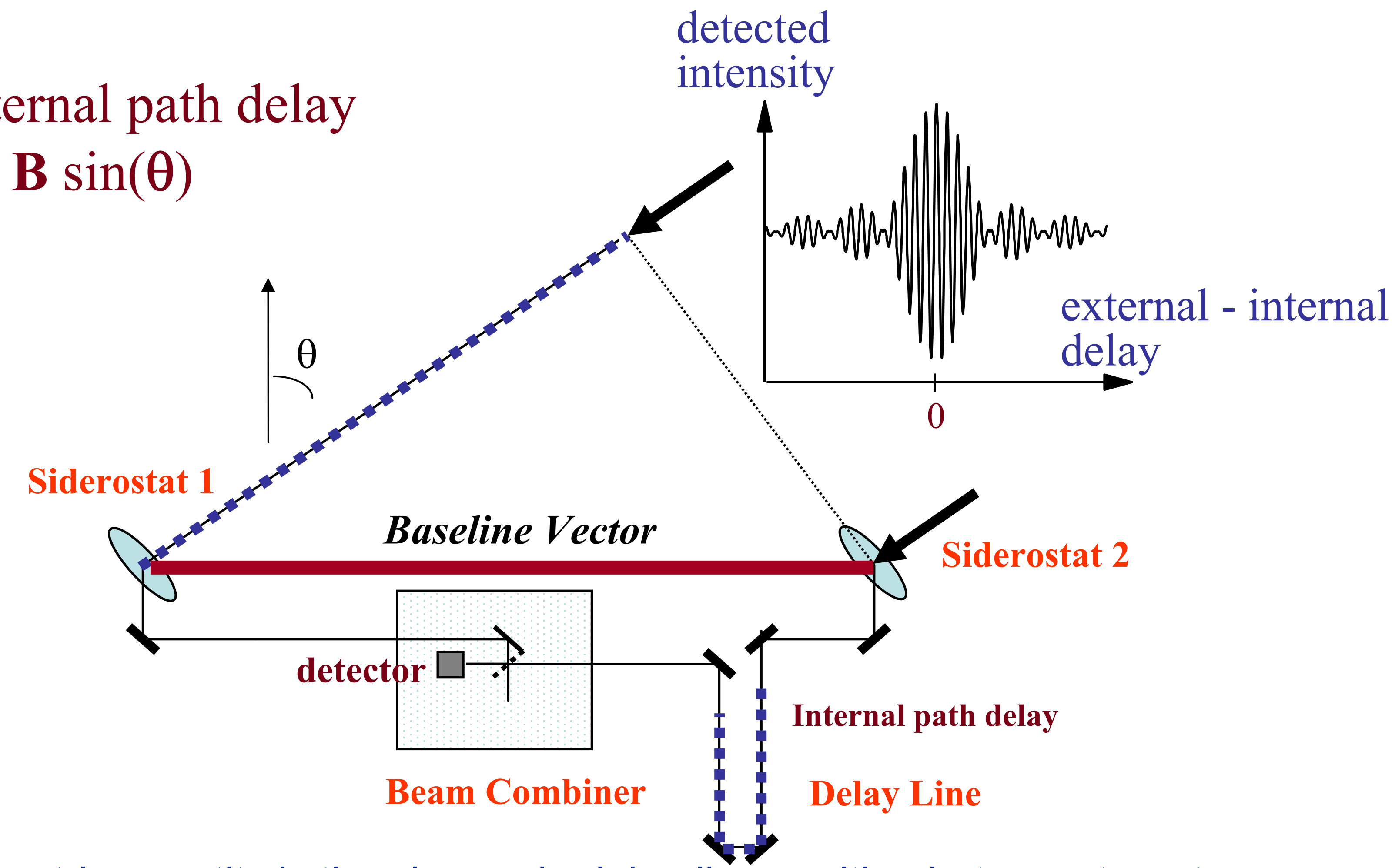
Astrometry with an Interferometer



Astrometric quantity is the change in delay-line position between targets

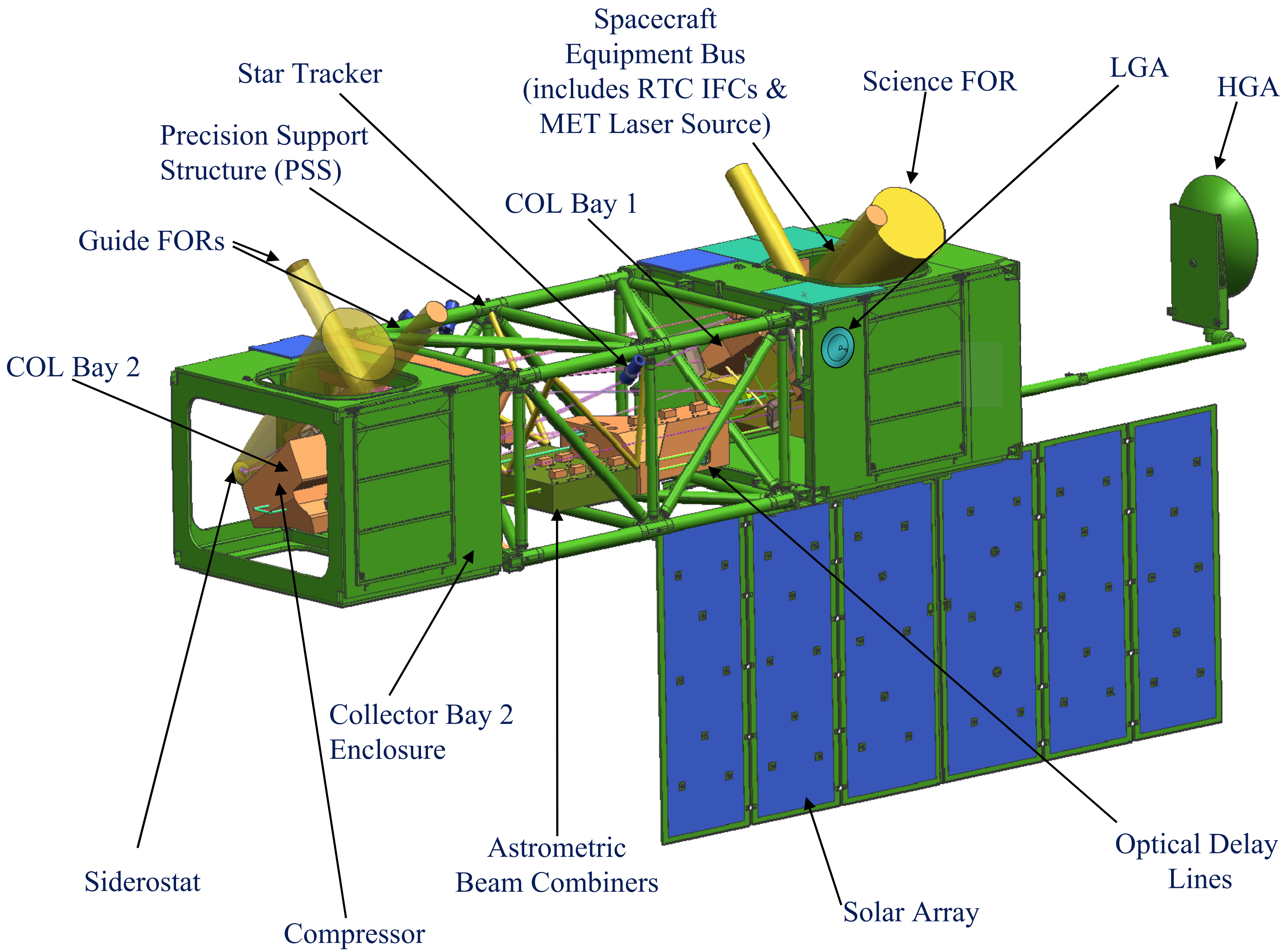
Astrometry with an Interferometer

External path delay
$\mathbf{x} = \mathbf{B} \sin(\theta)$



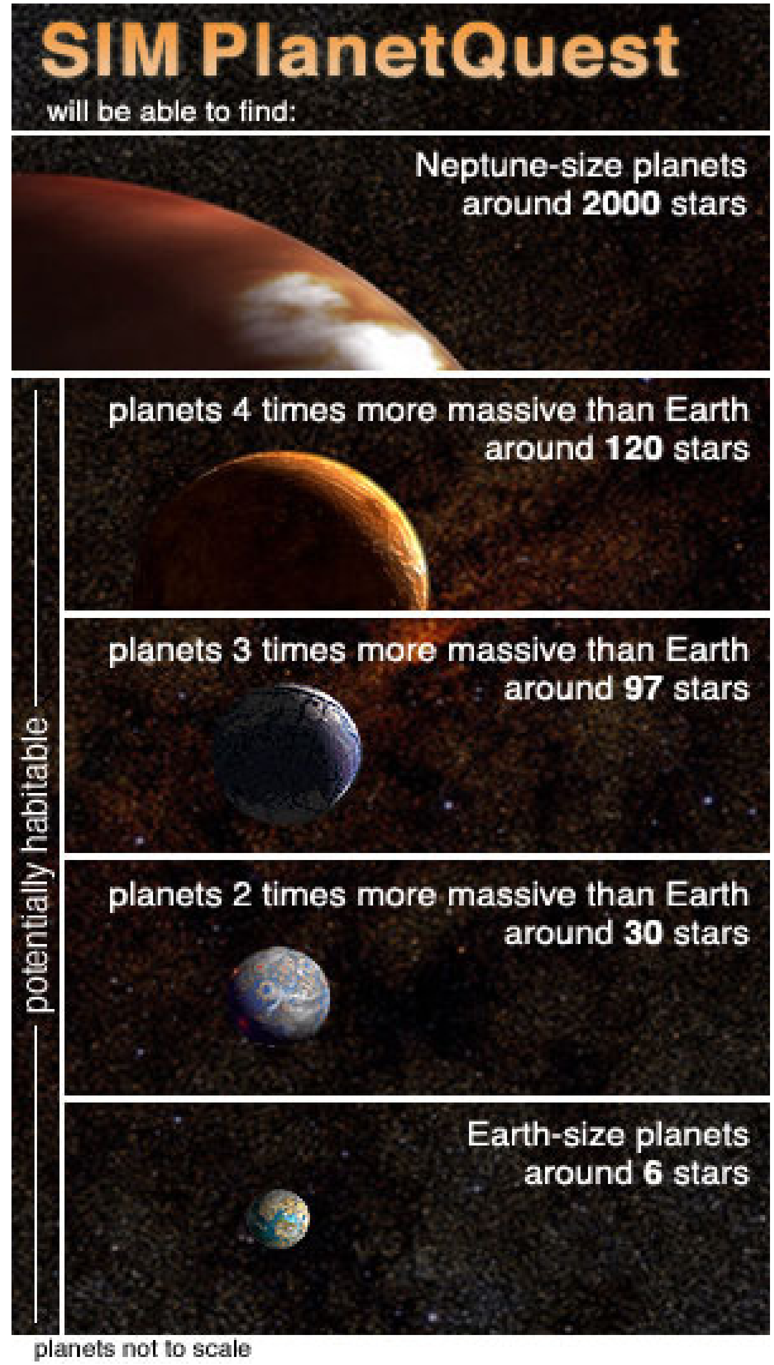
Astrometric quantity is the change in delay-line position between targets

Overall Configuration (deployed)



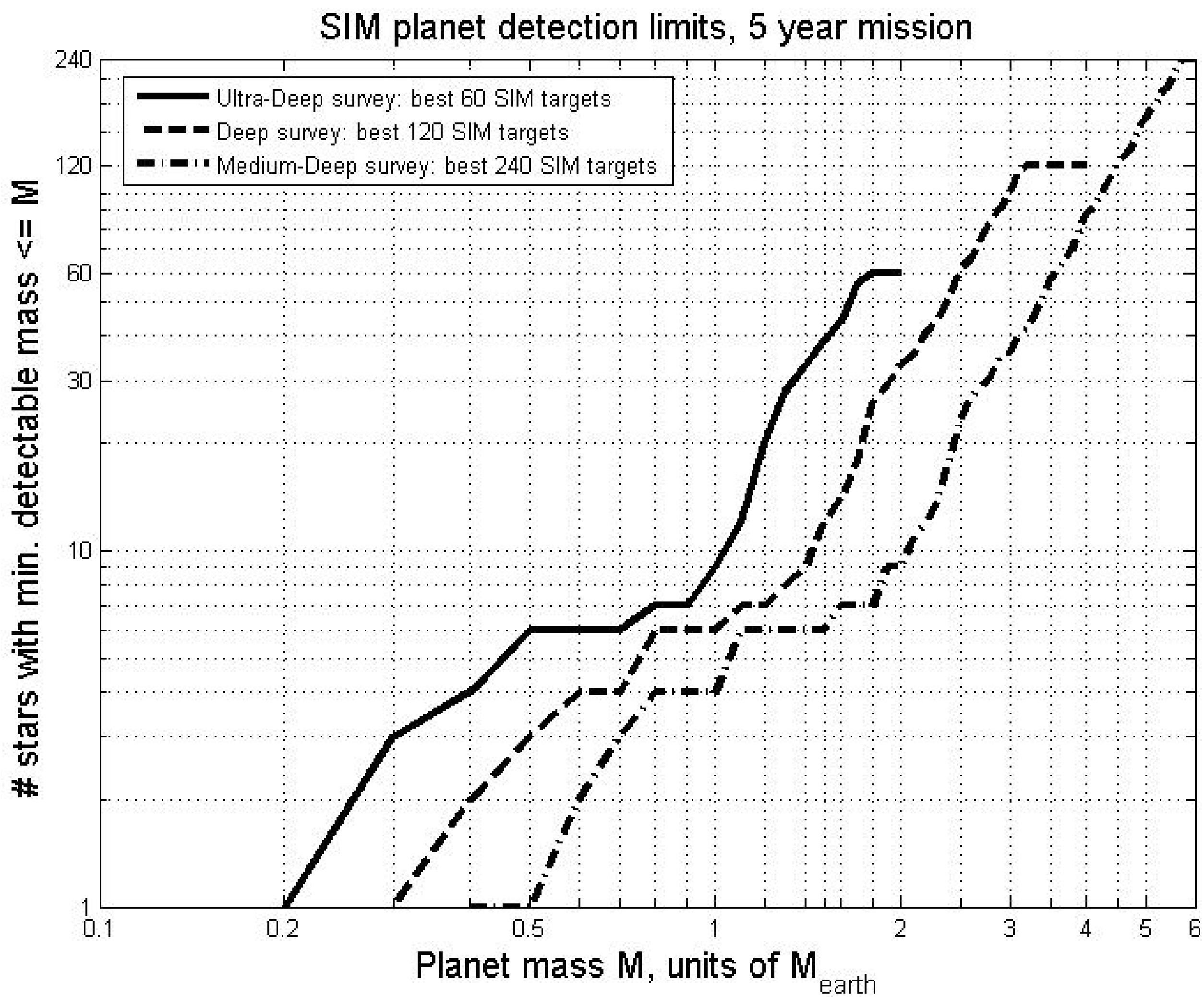
SIM Planet Finding Capabilities

- Potentially Habitable Planets are defined as:
  - Terrestrial planets in the habitable zone, where HZ = $(0.7 \text{ to } 1.5)(L_{star}/L_{sun})^{0.5}$ AU
  - Mass: $0.33\ M_{\oplus}$ to $10\ M_{\oplus}$
  - Radius: $0.5\ R_{\oplus}$ to $2.2\ R_{\oplus}$
  - Orbit: $e \leq 0.35$
- Deep search of 120 nearby stars within 30 parsecs
- Based on a 5 year science mission with
  - 1 µas single measurement accuracy with a 1.4 µas differential measurement in ~ 20 minutes, and
  - An allocation of 17% of SIM mission observing time



Planet detection with SIM - minimum masses

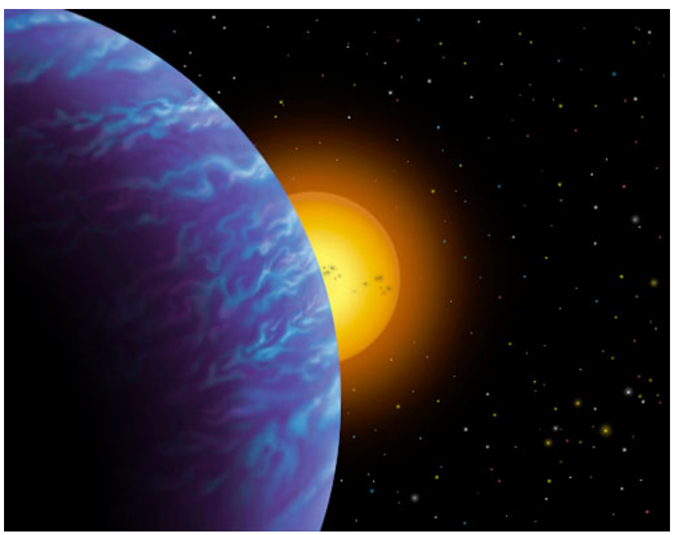
- For each candidate star in turn, evaluate the mimimum detectable mass within the habitable zone
- Rank-order the stars, then plot as a cumulative distribution



Searching for Terrestrial Planets with SIM

What We Don't Know

- Are planetary systems like our own common?
- What is the distribution of planetary masses?
  - **Only astrometry measures planet masses unambiguously**
- Are there low-mass planets in 'habitable zone' ?



A Broad Survey for Planets

- Is our solar system unusual?
- What is the range of planetary system architectures?
- Sample 2,000 stars within ~25 pc with sensitivity <<Jupiter mass

A Deep Search for Earths

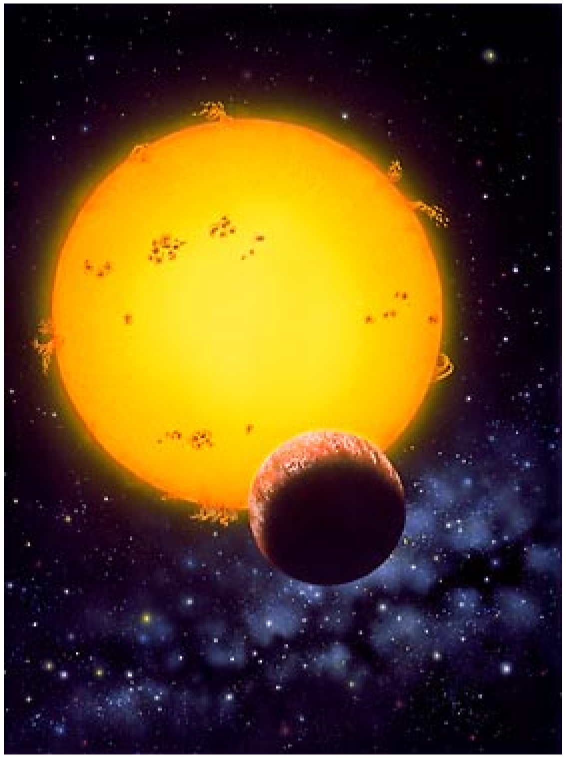
- Are there Earth-like (rocky) planets orbiting the nearest stars?
- Focus on ~250 stars like the Sun (F, G, K) within 10 pc
- Detection limit of ~3 M_e at 10 pc
- Sensitivity limit of ~1 M_e at 3 pc

Evolution of Planets

- How do systems evolve?
- Is the evolution conducive to the formation of Earth-like planets in stable orbits?
- Do multiple Jupiters form and only a few (or none) survive?

Planets around Young Stars

- What fraction of young stars have gas-giant planets?
  - Only SIM astrometry can find planets around young stars since active stellar atmospheres and rapid rotation preclude radial velocity or transit searches
- Do gas-giant planets form at the “water-condensation” line?
  - SIM will survey ~200 stars to a level adequate to find Jovian or smaller planets on orbits <1 AU to >5 AU around stars from 25-150 pc
- Does the incidence, distribution, and orbital parameters of planets change with age and protostellar disk mass?
  - Study of clusters with ages spanning 1-100 Myr to test orbital migration theories
  - Correlate with Spitzer results on disks (at 4-24 μm)
- Where, when, and how do terrestrial planets form ?
  - Understand the formation and orbital migration mechanisms of the giant planets
- ***No other technique before and possibly including TPF (RV, AO imaging, IR interferometry) can credibly claim to find planets down to Saturn-Jupiter mass within 1-10 AU of parent stars at 25-150 pc***



SIM PlanetQuest Science Team

Key Science Projects

Dr. Geoffrey Marcy	U. California, Berkeley	Planetary Systems
Dr. Michael Shao	NASA/JPL	Extrasolar Planets
Dr. Charles Beichman	NASA/JPL	Young Planetary Systems and Stars
Dr. Andrew Gould	Ohio State University	Astrometric Micro-Lensing
Dr. Edward Shaya	U. Maryland	Dynamic Observations of Galaxies
Dr. Kenneth Johnston	U.S. Naval Observatory	Reference Frame-Tie Objects
Dr. Brian Chaboyer	Dartmouth College	Population II Distances & Globular Clusters Ages
Dr. Todd Henry	Georgia State University	Stellar Mass-Luminosity Relation
Dr. Steven Majewski	University of Virginia	Measuring the Milky Way
Dr. Ann Wehrle	MSC/Caltech	Active Galactic Nuclei

Mission Scientists

Dr. Guy Worthey	Washington State University	Education & Public Outreach Scientist
Dr. Andreas Quirrenbach	U. California, San Diego	Data Scientist
Dr. Stuart Shaklan	NASA/JPL	Instrument Scientist
Dr. Shrinivas Kulkarni	Caltech	Interdisciplinary Scientist
Dr. Ronald Allen	Space Telescope Science Inst.	Synthesis Imaging Scientist

Only Principal Investigators listed. Including co-investigators the SIM Science Team has 86 members.

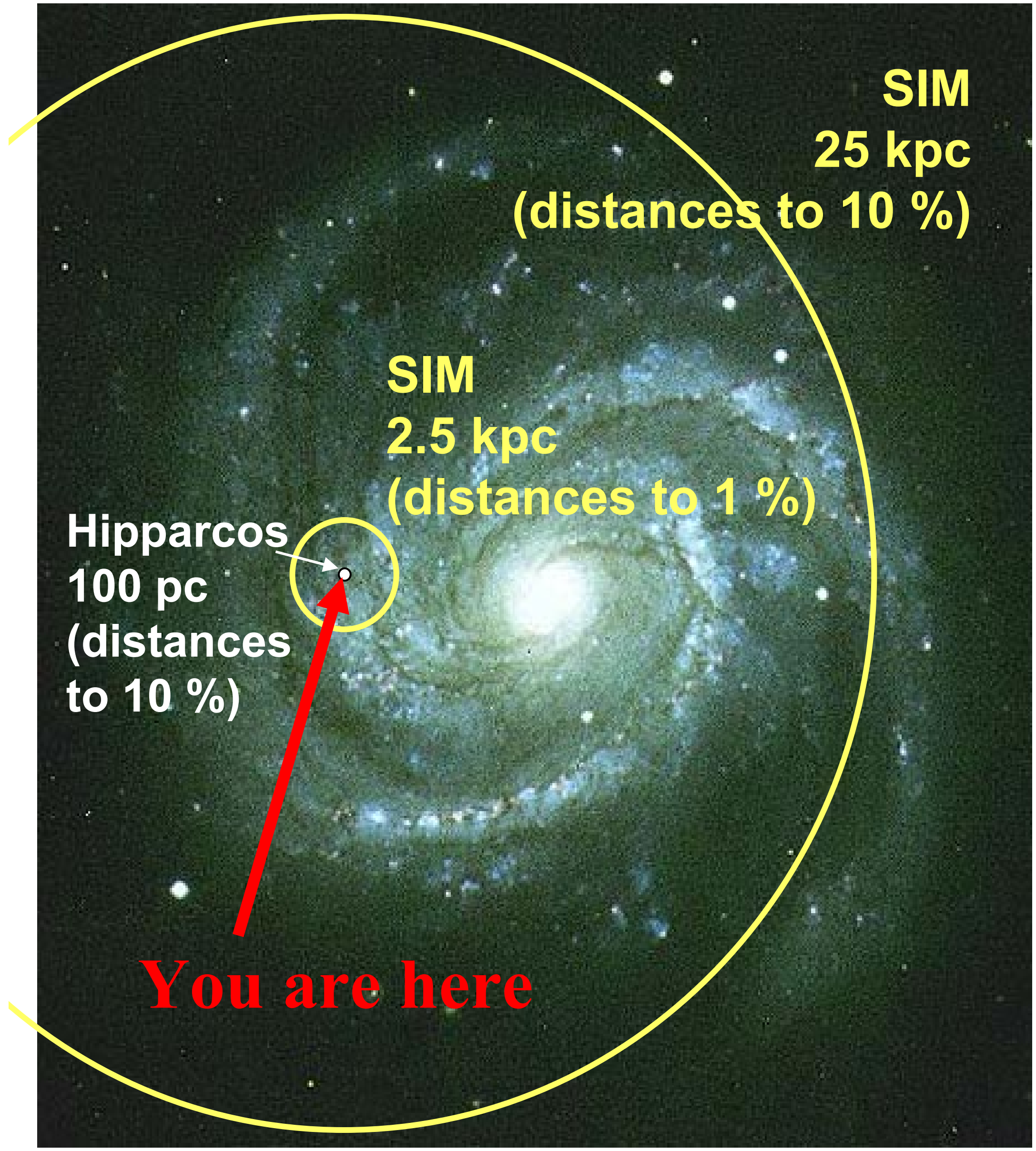
SIM Astrophysics

- SIM does much more than just planet finding with 60% of SIM science time for non-planetary astrophysics
- High precision astrometry applied to definitive studies of
  - Distance scale problem
  - Age scale (star clusters)
  - Mass-luminosity relation
  - Galactic structure / stellar populations / dynamics
  - Dark matter (from galaxy scale to MACHO candidates)
  - Local group dynamics / cosmology
  - AGN structure
  - Black holes, other stellar remnants, x-ray binaries
  - Establish the inertial frame 50x more precisely than ICRF
  - Target of opportunity capability
- PLUS: 1/3 of total science time *still available* for new cutting edge science goals through a Guest Observer program

SIM's Reach Extends Across our Entire Galaxy to do "Precision Astrophysics"

What makes SIM unique:

- Extreme astrometric precision
  - 4 µas (microarcsec) positions
  - 4 µas/yr proper motions
  - 1 µas differential positions
- Ability to observe faint targets
  - V <~ 20
- Flexible scheduling
  - optimize for specific science objectives



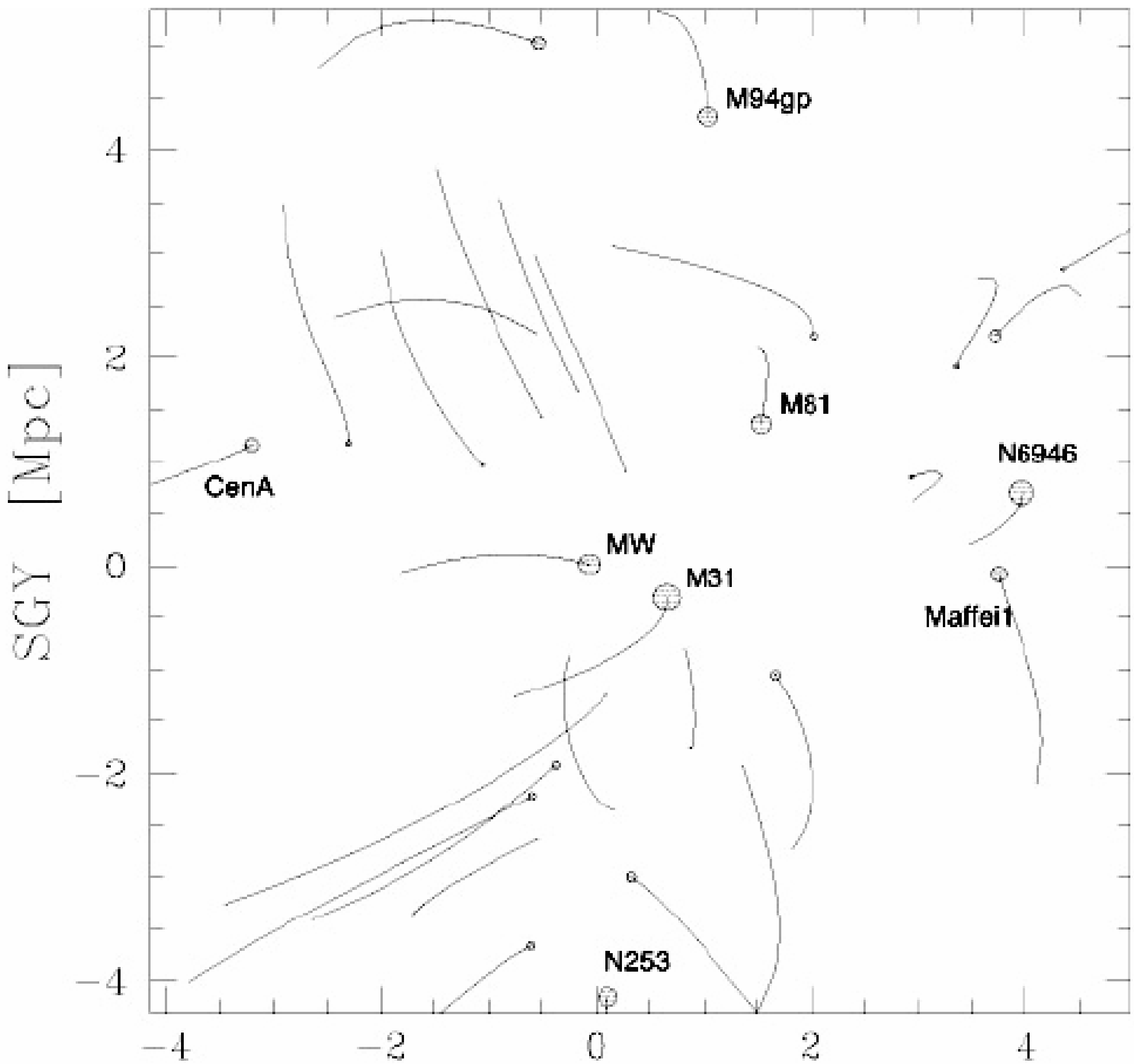
Dynamics of Galaxy Groups within 5 Mpc

Simulation from dynamical model

- Can't verify model because only 1-D velocity info is available (RV)

SIM will provide critical data for improving the models

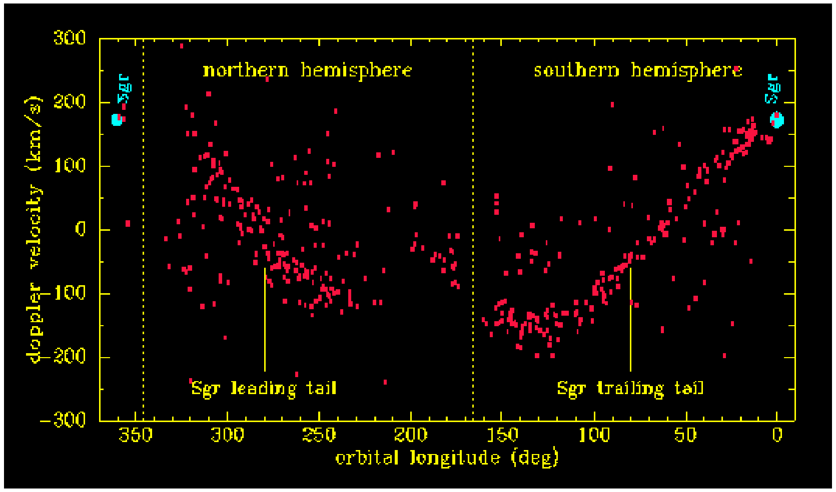
- SIM will measure current 2-D velocities across the sky
- Models will then sample the full 6-D phase space



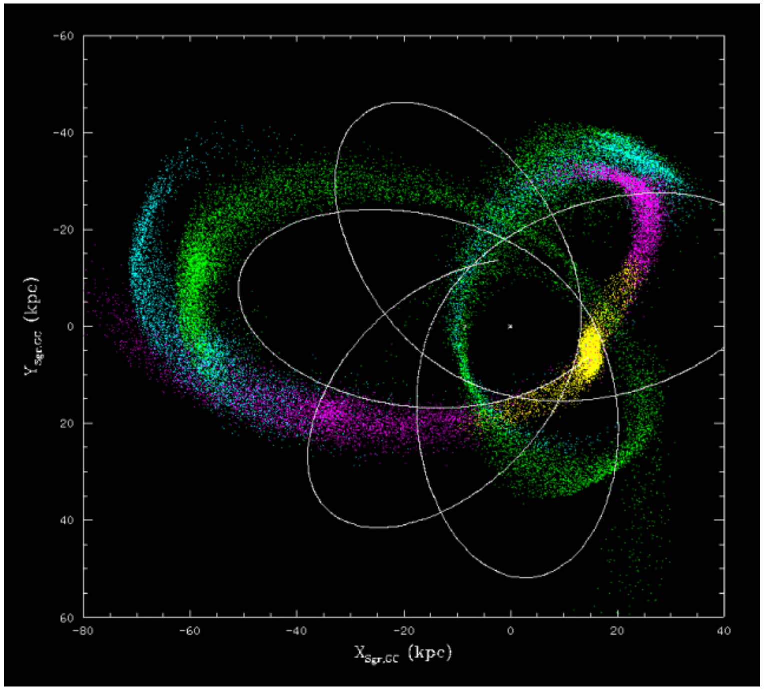
Simulated 'time-lapse' photo of 30 galaxies closest to our Milky Way (1-billion year exposure)

Galactic tidal tails

- Much new info on Sgr Dwarf system
  - Initial 2MASS work reveals >360deg arms
  - Radial-velocity constraints



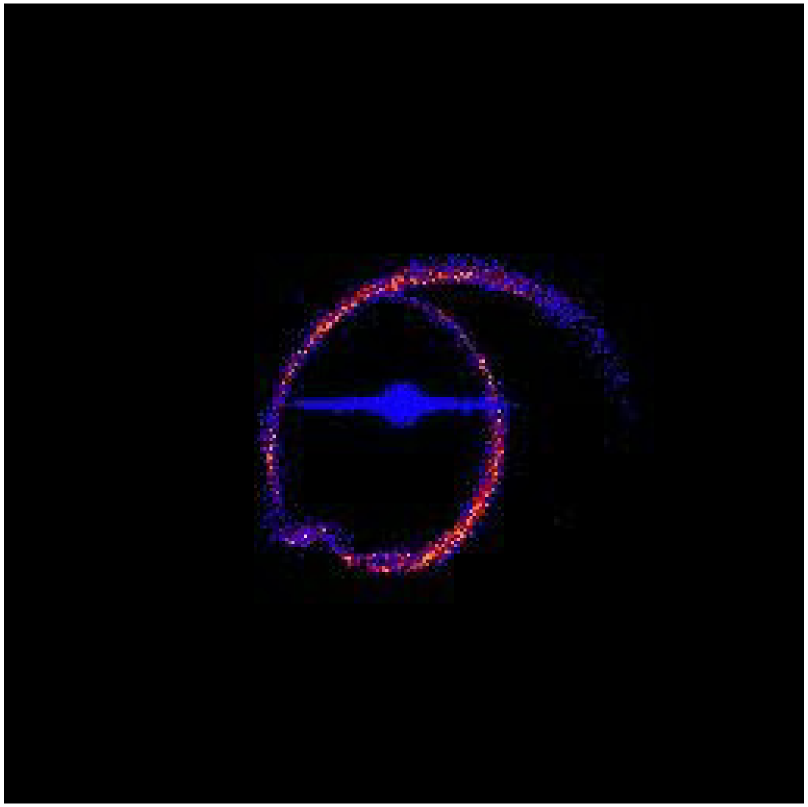
  - With only 4-D constraints, problems/contradictions remain:
    - We need all 6-D measurements
  - Modeling of Sgr and Galactic halo
  - Leading Arm RVs are “wrong”
  - Prolate vs. Oblate ambiguity



Dark Halo of our Galaxy

- 'Dwarf spheroidal' galaxy orbits the Milky Way
- Gravitational forces pull out 'tidal tails' of stars
- The orbits of these tails trace the past history of the dwarf
- They also trace the mass distribution of the Milky Way
- They are dynamically 'cold'

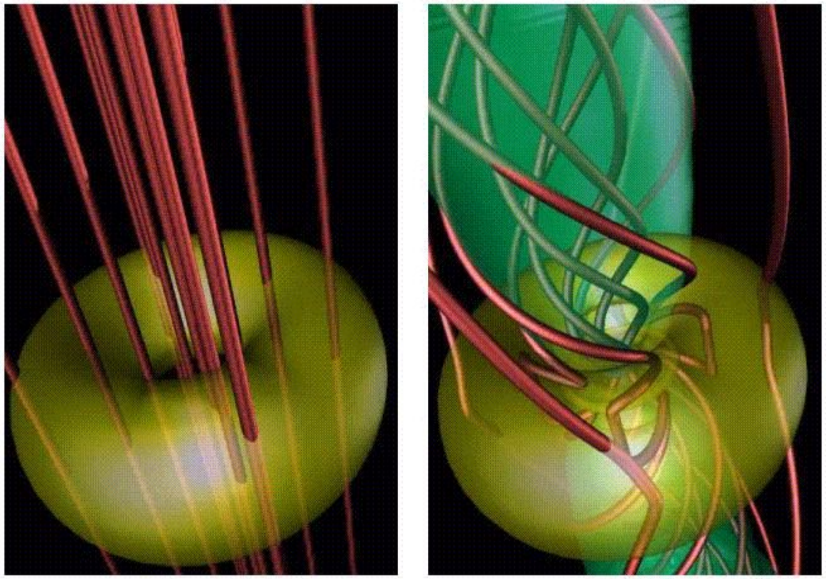
- SIM provides:
  - Astrometric motions of stars out to > 20 kpc
- Why SIM?
  - Need astrometric accuracy
  - *and* sensitivity



Simulation by Kathryn Johnston (Wesleyan University)

Probing Active Galactic Nuclei with Astrometry

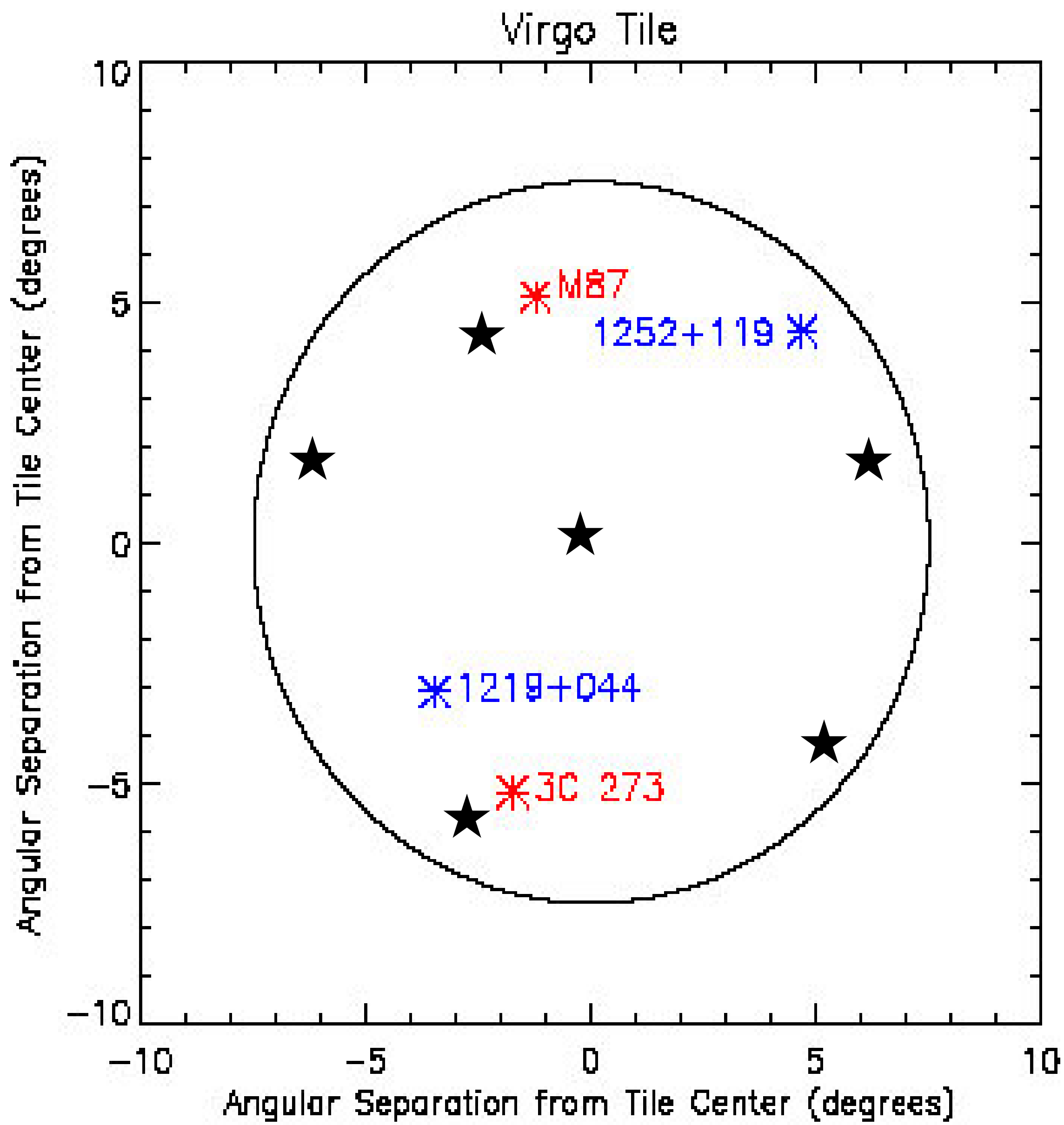
1. Does the most compact non-thermal optical emission from an AGN come from an accretion disk or from a relativistic jet?
2. Do the cores of galaxies harbor binary supermassive black holes remaining from galaxy mergers ?
3. Is the separation of the radio core and optical photocenter of the quasars used for the reference frame tie stable? Or does it change on the timescales of their photometric variability?



- SIM measurements:
  - *Flexible scheduling* - coordinated campaigns of flare outbursts with VLBI, X-ray telescopes
  - Relative astrometry between QSO and reference stars (or other QSOs)
  - Astrometric shifts as a function of wavelength
  - Global astrometry: motion of QSOs relative to global reference frame
    - Departures from Hubble flow: $z = 0.1$, V = 10,000 km/s → 6 µas / yr

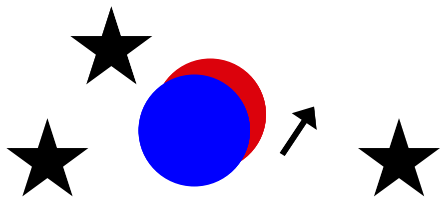
Sample ‘tile’ for relative astrometry

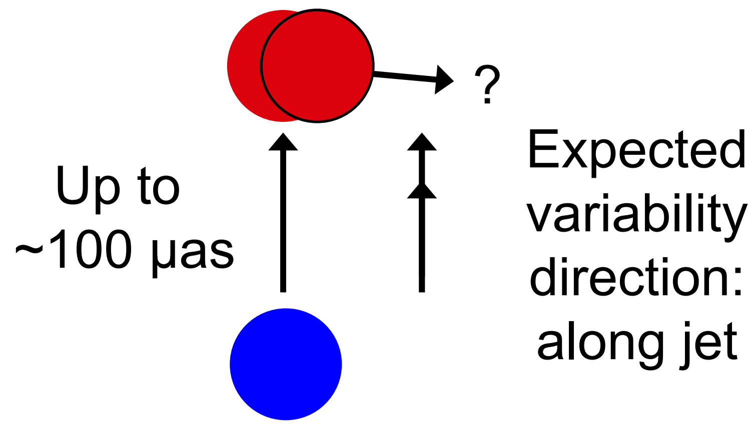
- SIM instrument field (‘tile’) is 15° diameter
- Select tile centers for objects of interest
- ‘Virgo tile’ contains:
  - M87
  - 3C 273
  - Two ICRF quasars
  - ~6 halo K-giants



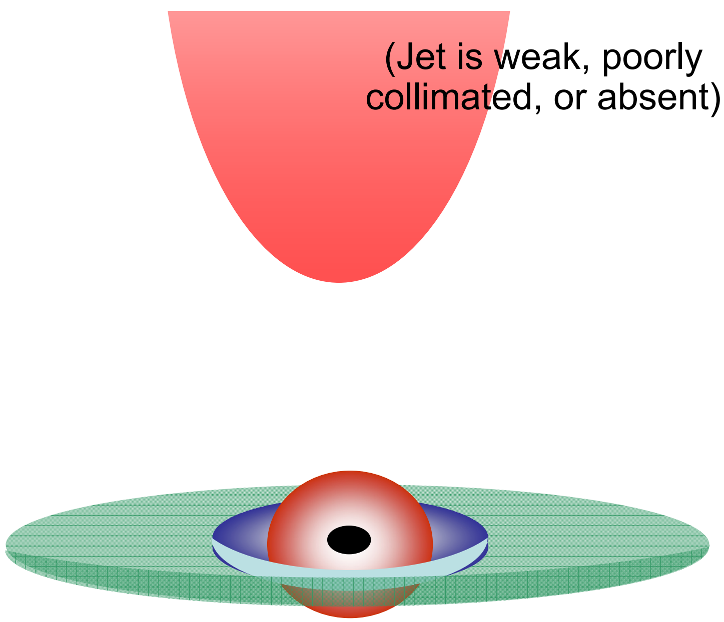
Astrometric signatures of AGN

Expect no color shift, (or small shift ~1-5 µas) with no preferred axis. Variability has no preferred direction

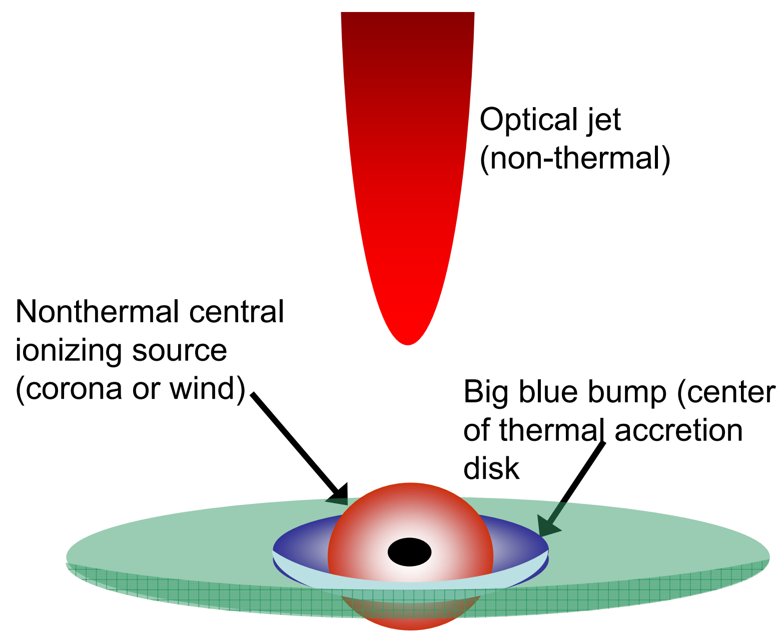




Radio-quiet AGN

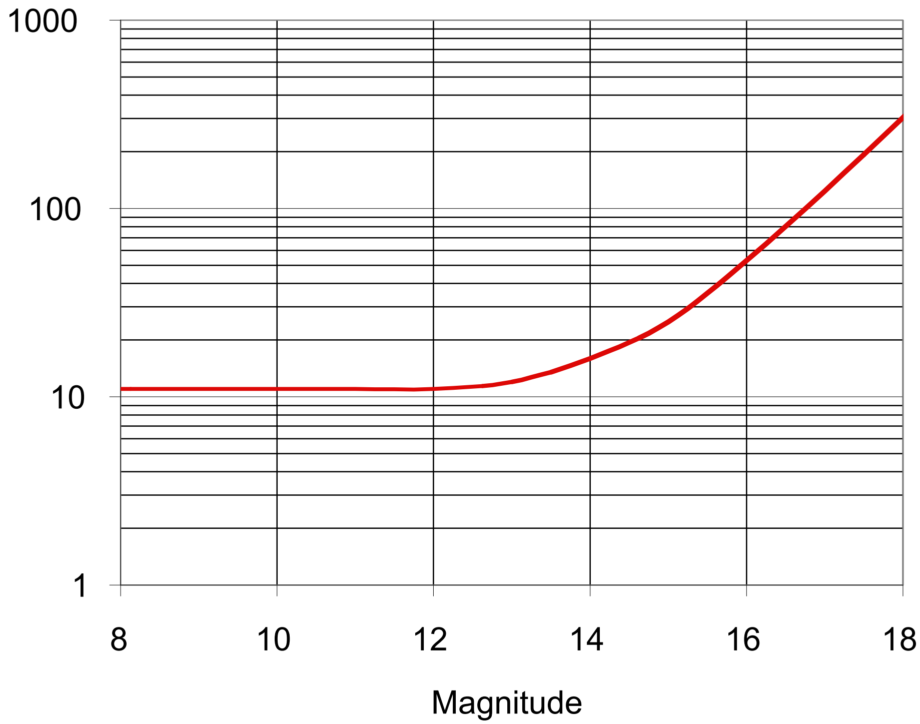


Radio-loud AGN



Snapshot Observing Mode: "Astrometry for the masses"

- *You don't need to be a black-belt astrometrist to use this mode*
- Mode will deliver the "5 standard astrometric parameters":
  - Position (RA, dec), parallax, proper motion (RA, dec)
  - Accuracy ~10-50 μas, and magnitude range V ~ 8-17
- Large number of targets (total ~20,000)
- Available though the *Guest Observer Program* - about 1/4 of SIM time



10 minutes per target, spread over
2 years; 5 visits x 2 coordinates

SIM Technology Development is Complete !

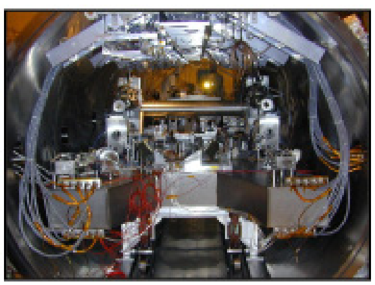
- Technology plan laid out in mid-1990s
- NASA HQ and SIM project laid out 8 Key Technology Gates in 2001
  - 4 Gates prior to Phase B start; 4 more Gates prior to Phase C/D start
- All 8 Technology Gates were completed on schedule with external peer review
- External reviewers & NASA sponsor have concurred: *Technology is complete*
- NASA & Project have established 9 Engineering milestones for Phase B/C/D

Component Technology 1-4
Complete!
Aug 2001

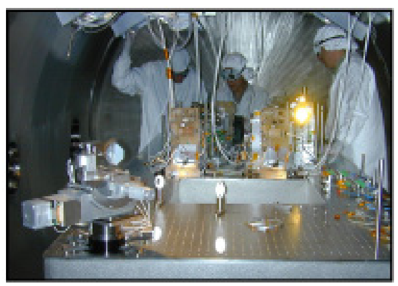
Subsystem/System Testbeds 5-7
Complete!
June 2004

Modeling/Testbed Integration 8
Complete!
July 2005

Goal-Level Performance & TRL-6 Maturity Has Been Demonstrated



MAM



KITE

Subsystem-level Testbeds

STB-3

System-level Testbed

TOM-3

Modeling/Testbed Integration

SIM will:

- Search ~250 nearby stars for terrestrial planets
- Study the diversity of planetary systems around various types of stars
- Advance our understanding of planetary system evolution by studying planets around young stars
- Study the Astrophysics of
    - Stars of all types in our Galaxy
    - The structure of our Galaxy
    - Distant Active Galactic Nuclei

A particular attraction of SIM is its ***dual capability:***

- " the detection of planets through narrow-angle astrometry and
- " the mapping of the structure of our Galaxy and nearby galaxies through wide-angle astrometry."

"Astronomy and Astrophysics in the New Millennium"
2001 NRC Decade Report
C. McKee & J. Taylor, Editors